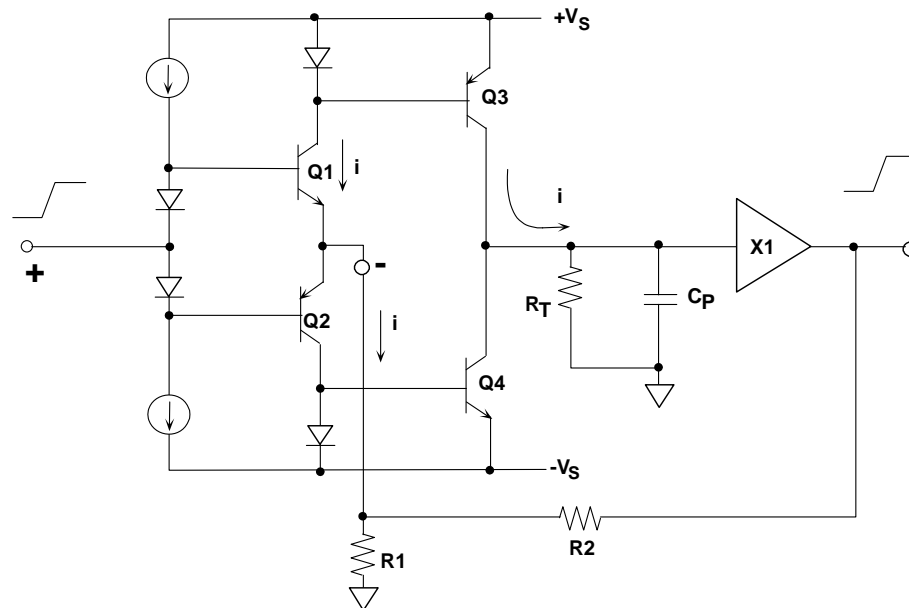


## High Speed Current Feedback Op Amps

### CFB OP AMP SIMPLIFIED CIRCUIT AND MODEL

We will now examine in more detail the current feedback (CFB) op amp topology which is very popular in high speed op amps. As mentioned previously, the circuit concepts were introduced decades ago, however modern high speed complementary bipolar processes are required to take full advantage of the architecture.

It has long been known that in bipolar transistor circuits, currents can be switched faster than voltages, other things being equal. This forms the basis of non-saturating emitter-coupled logic (ECL) and devices such as current-output DACs. Maintaining low impedances at the current switching nodes helps to minimize the effects of stray capacitance, one of the largest detriments to high speed operation. The current mirror is a good example of how currents can be switched with a minimum amount of delay.



**Figure 1: Simplified Current Feedback (CFB) Op Amp**

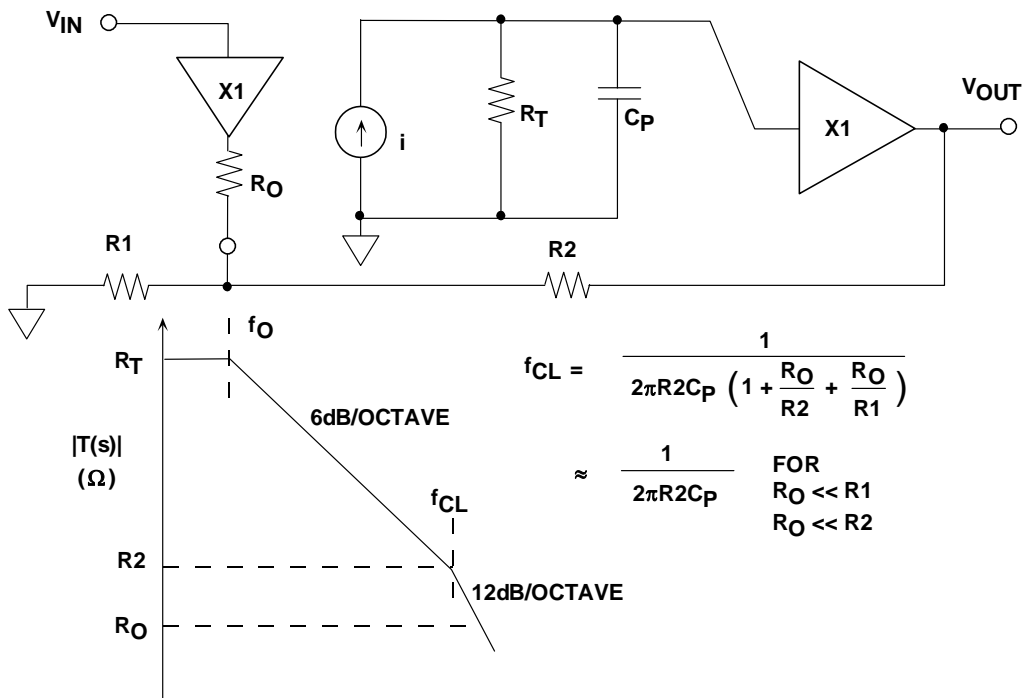
The current feedback op amp topology is simply an application of these fundamental principles of current steering. A simplified CFB op amp is shown in Figure 1 above. The non-inverting input is high impedance and is buffered directly to the inverting input through the complementary emitter follower buffers Q1 and Q2. Note that the inverting input impedance is very low (typically 10 to 100  $\Omega$ ), because of the low emitter resistance (ideally, would be zero). This is a fundamental difference between a CFB and a VFB op amp, and also a feature that gives the CFB op amp some unique advantages.

The collector outputs of Q1 and Q2 drive current mirrors, which mirror the inverting input current to the high impedance node, modeled by  $R_T$  and  $C_P$ . The high impedance node is buffered by a complementary unity gain emitter follower. Feedback from the output to the inverting input acts to force the inverting input *current* to zero, hence the term *Current Feedback*. Note that in an ideal case, for zero inverting input impedance, no small signal voltage can exist at this node, only small-signal current.

Now, consider a positive step voltage applied to the non-inverting input of the CFB op amp. Q1 immediately sources a proportional current into the external feedback resistors creating an *error* current, which is mirrored to the high impedance node by Q3. The voltage developed at the high impedance node is equal to this current multiplied by the equivalent impedance. This is where the term *transimpedance op amp* originated, since the transfer function is an impedance, rather than a unitless voltage ratio as in a traditional VFB op amp.

Note also that the error current delivered to the high impedance node is not limited by the input stage tail current. In other words, unlike a conventional VFB op amp, *there is no slew-rate limitation in an ideal CFB op amp*. The current mirrors supply *current-on-demand* from the power supplies. The negative feedback loop then forces the output voltage to a value that reduces the inverting input error current to zero.

The model for a CFB op amp is shown in Figure 2, along with the corresponding Bode plot. The Bode plot is plotted on a log-log scale, and the open-loop gain is expressed as a transimpedance,  $T(s)$ , with units of ohms.



**Figure 2: CFB Op Amp Model and Bode Plot**

The finite output impedance of the input buffer is modeled by  $R_O$ . The input error current is  $i$ . By applying the principles of negative feedback, we can derive the expression for the op amp transfer function:

$$\frac{v_{out}}{v_{in}} = \frac{1 + \frac{R_2}{R_1}}{1 + j\omega C_P R_2 \left( 1 + \frac{R_O}{R_2} + \frac{R_O}{R_1} \right)}. \quad \text{Eq. 1}$$

At the op amp 3 dB closed-loop bandwidth frequency,  $f_{cl}$ , the following is true:

$$2\pi f_{cl} C_P R_2 \left( 1 + \frac{R_O}{R_2} + \frac{R_O}{R_1} \right) = 1. \quad \text{Eq. 2}$$

Solving for  $f_{cl}$ :

$$f_{cl} = \frac{1}{2\pi C_P R_2 \left( 1 + \frac{R_O}{R_2} + \frac{R_O}{R_1} \right)}. \quad \text{Eq. 3}$$

For the condition  $R_O \ll R_2$  and  $R_1$ , the equation simply reduces to:

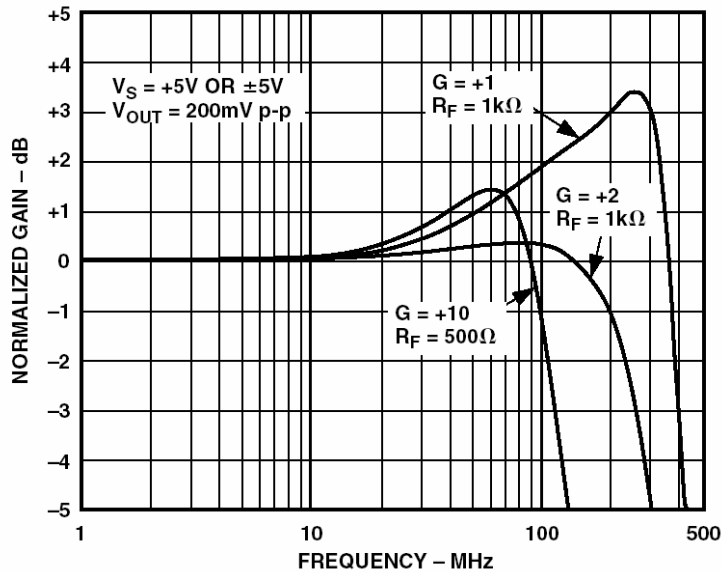
$$f_{cl} = \frac{1}{2\pi C_P R_2}. \quad \text{Eq. 4}$$

Examination of this equation quickly reveals that *the closed-loop bandwidth of a CFB op amp is determined by the internal dominant pole capacitor,  $C_P$ , and the external feedback resistor  $R_2$ , and is independent of the gain-setting resistor,  $R_1$ .* This ability to maintain constant bandwidth independent of gain makes CFB op amps ideally suited for wideband programmable gain amplifiers.

Because the closed-loop bandwidth is inversely proportional to the external feedback resistor,  $R_2$ , a CFB op amp is usually optimized for a specific  $R_2$ . Increasing  $R_2$  from its optimum value lowers the bandwidth, and decreasing it may lead to oscillation and instability because of high frequency parasitic poles.

## PERFORMANCE OF MODERN CFB OP AMPS

The frequency response of the [AD8011](#) CFB op amp is shown in Figure 3 for various closed-loop values of gain (+1, +2, and +10). Note that even at a gain of +10, the closed-loop bandwidth is still greater than 100 MHz. The peaking which occurs at a gain of +1 is typical of wideband CFB op amps used in the non-inverting mode, and is due primarily to stray capacitance at the inverting input. This peaking can be reduced by sacrificing bandwidth, by using a slightly larger feedback resistor.



**Figure 3: [AD8011](#) Frequency Response,  $G = +1, +2, +10$**

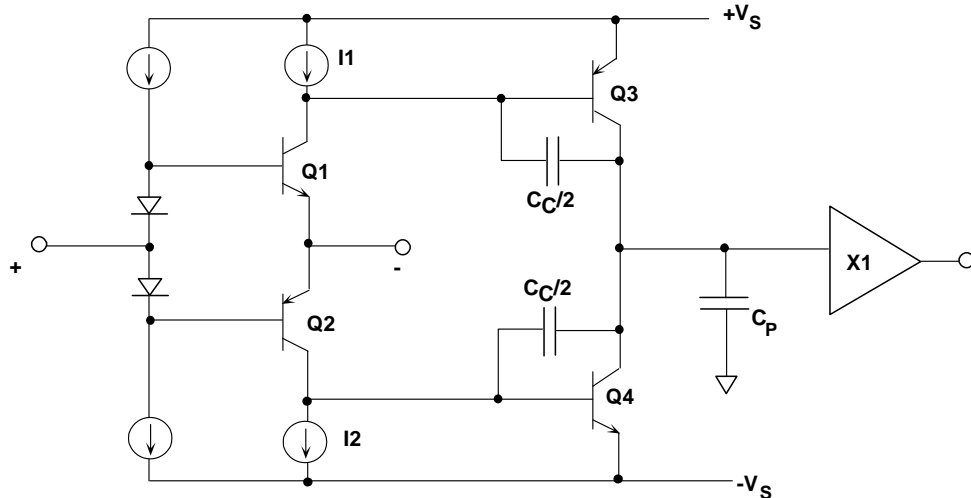
The AD8011 CFB op amp (introduced in 1995) still represents state-of-the-art performance, and key specifications are shown in Figure 4 below.

- ◆ **1mA Power Supply Current (+5V or ±5V)**
- ◆ **300MHz Bandwidth ( $G = +1$ )**
- ◆ **2000 V/μs Slew Rate**
- ◆ **29ns Settling Time to 0.1%**
- ◆ **Video Specifications ( $G = +2$ )**
  - Differential Gain Error 0.02%
  - Differential Phase Error 0.06°
  - 25MHz 0.1dB Bandwidth
- ◆ **Distortion**
  - 70dBc @ 5MHz
  - 62dBc @ 20MHz
- ◆ **Fully Specified for ±5V or +5V Operation**

**Figure 4: AD8011 Key Specifications**

## ADVANCES IN CFB OP AMP TOPOLOGY

Traditional current feedback op amps have been limited to a single gain stage, using current-mirrors. The [AD8011](#) (and also others in this family) unlike traditional CFB op amps, use a *two-stage gain configuration*, as shown in Figure 5 below.



**Figure 5: Simplified Two-Stage Current Feedback Op Amp**

Until the advent of the AD8011, fully complementary two-gain stage CFB op amps had been impractical because of their high power dissipation. The AD8011 employs a patented second gain stage consisting of a pair of complementary amplifiers (Q3 and Q4). Note that they are not connected as current mirrors but as grounded-emitter gain stages. The detailed design of current sources (I1 and I2), and their respective bias circuits are the key to the success of the two-stage CFB circuit; they keep the amplifier's quiescent power low, yet are capable of supplying *current-on-demand* for wide current excursions required during fast slewing. A further advantage of the two-stage amplifier is the higher overall bandwidth (for the same power), which means lower signal distortion and the ability to drive heavier external loads.

A brief summary of some popular current feedback op amps is given in Figure 6. The parts are listed in order of decreasing power supply current.

**LISTED IN ORDER OF DECREASING SUPPLY CURRENT**

PART #	I <sub>SY</sub> / AMP	BANDWIDTH	SLEWRATE
AD8009 (1)	16.0mA	1000MHz	5500V/μs
AD8000 (1)	14.3mA	1580MHz	4100V/μs
AD8002 (2)	11.5mA	600MHz	1200V/μs
AD8003 (3)	10.2mA	1650MHz	3800V/μs
ADA4861-3 (3)	6.83mA	730MHz	680V/μs
AD8001 (1)	5.0mA	880MHz	1000V/μs
AD8013 (3)	4.0mA	480MHz	1000V/μs
AD8011 (1)	1.3mA	400MHz	3500V/μs

Number in ( ) Indicates Single, Dual, Triple, or Quad

**Figure 6: Performance of Selected CFB Op Amps**

**REFERENCES**

1. Hank Zumbahlen, *Basic Linear Design*, Analog Devices, 2006, ISBN: 0-915550-28-1. Also available as [\*Linear Circuit Design Handbook\*](#), Elsevier-Newnes, 2008, ISBN-10: 0750687037, ISBN-13: 978-0750687034. Chapter 1.
2. Walter G. Jung, *Op Amp Applications*, Analog Devices, 2002, ISBN 0-916550-26-5, Also available as [\*Op Amp Applications Handbook\*](#), Elsevier/Newnes, 2005, ISBN 0-7506-7844-5. Chapter 1.

Copyright 2009, Analog Devices, Inc. All rights reserved. Analog Devices assumes no responsibility for customer product design or the use or application of customers' products or for any infringements of patents or rights of others which may result from Analog Devices assistance. All trademarks and logos are property of their respective holders. Information furnished by Analog Devices applications and development tools engineers is believed to be accurate and reliable, however no responsibility is assumed by Analog Devices regarding technical accuracy and topicality of the content provided in Analog Devices Tutorials.